HYDROGEN PRODUCTION GHG CONTROL TECHNOLOGY REVIEW

REPORT BY WORLEY CONSULTING

REPORT GOAL & CONTENTS

- **Goal**: analyze the state of technologies for reducing or eliminating greenhouse gas (GHG) emissions at new and existing hydrogen production facilities.

- Contents
  - Legislation and Regulation Background
  - Technology Overview
  - GHG Emissions Reductions Pathways
  - Economic Analysis
  - Environmental Impact and Conclusions

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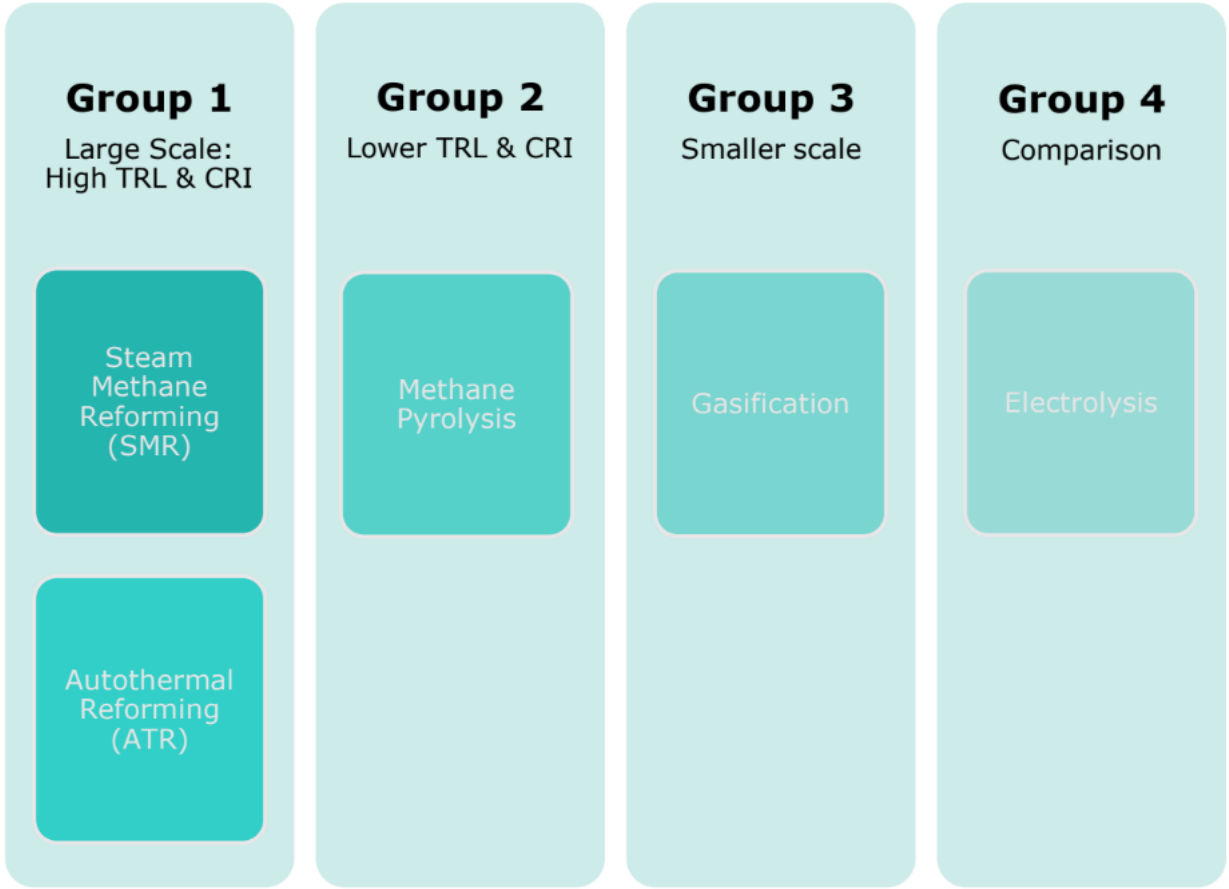
Hydrogen Production Technology Categories

The hydrogen production technologies analyzed in this study range from traditional to emerging These have been classified into 4 distinct groups based on technology maturity and commercial readiness using the indicative metrics of technology readiness level (TRL) and commercial readiness index (CRI).



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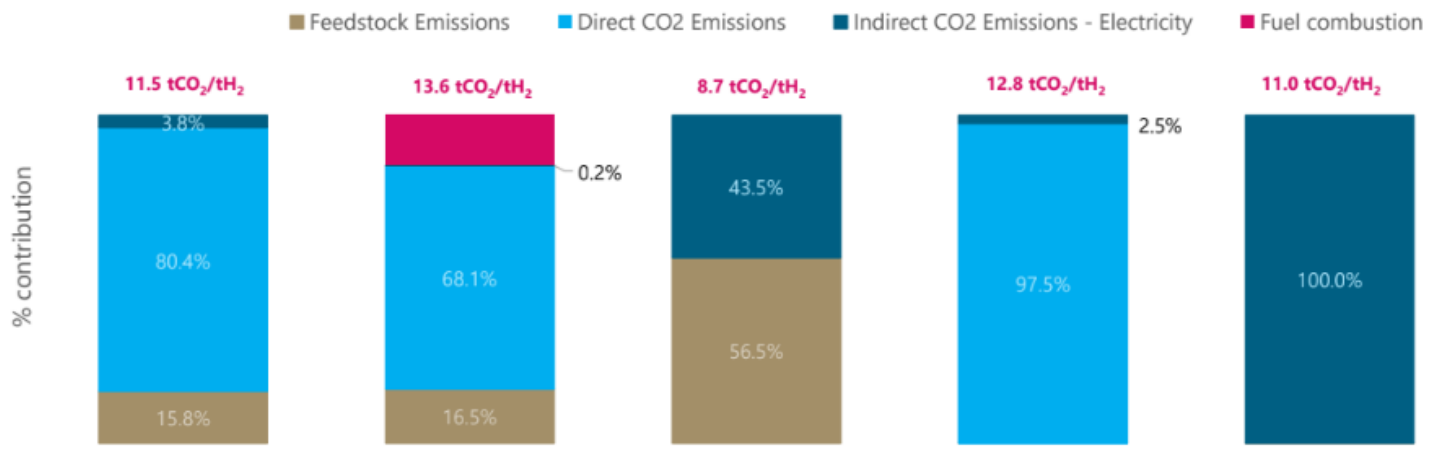
Unabated Emissions from Hydrogen Production & Reduction Levers

A well-to-gate approach is used to define the boundary limits for the emissions calculations. For the purposes of this study, boundary limit properties do not include additional compression or purification of hydrogen beyond standard levels for a given production technology.



Lever	ATR	SMR	Methane Pyrolysis	Biomass Gasification*	Alkaline Electrolysis
Process Optimization	-	●	-	-	-
Low Carbon feedstock	-	-	-	●	-
Low Carbon utility supply	●	●	●	●	●
Carbon Capture	●	●	-	●	-

Note: Figure is based on grid supplied electricity and not renewables; for gasification, base case feed is assumed to be non-biogenic

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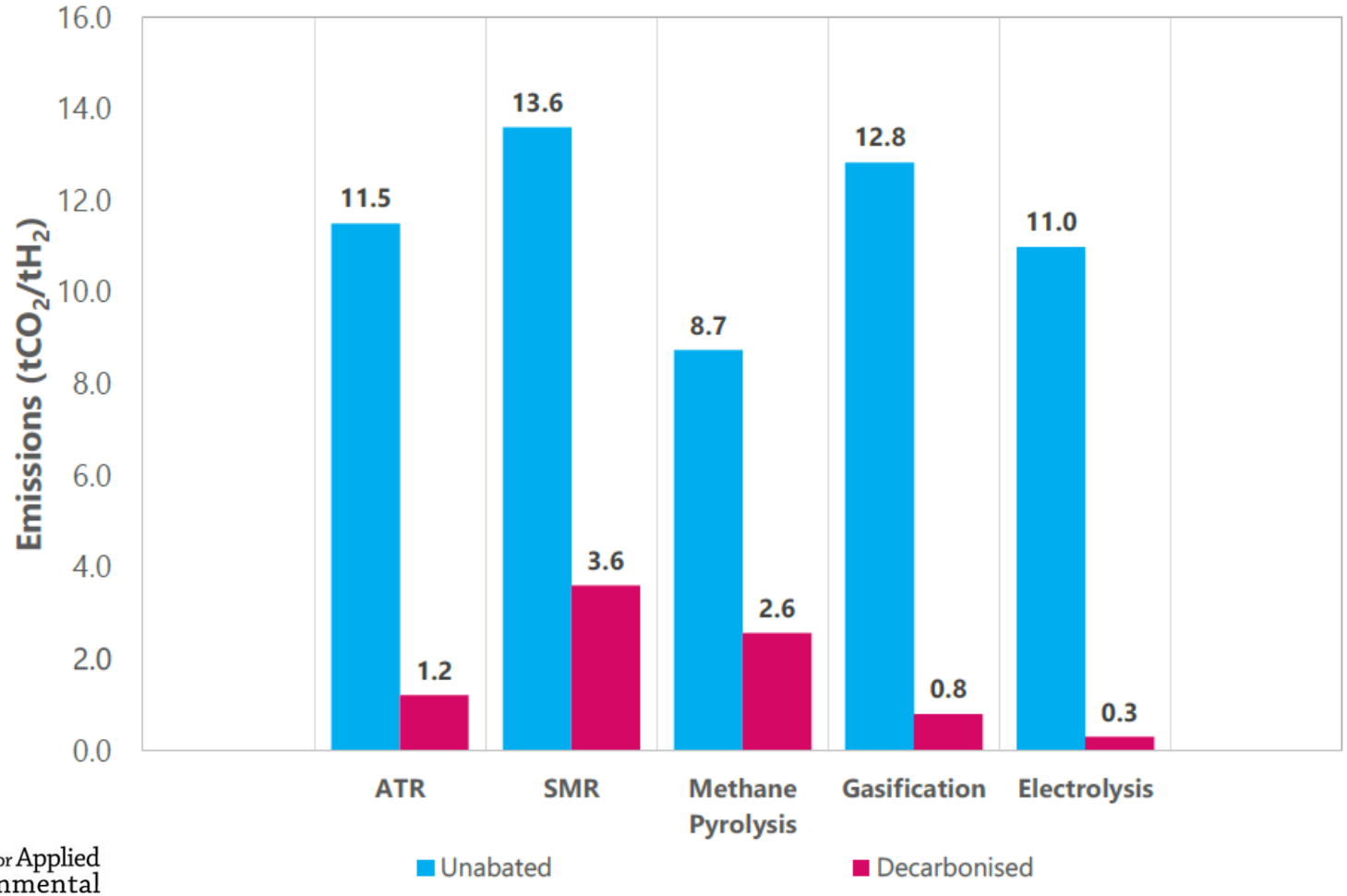
Comparative Analysis of Emissions Reduction Potential

Application of GHG reduction technologies to the unabated cases could achieve the following order from lowest to highest carbon intensity: electrolysis, gasification, ATR, methane pyrolysis and finally SMR. Methane pyrolysis has the lowest potential for GHG reduction while gasification has the highest.



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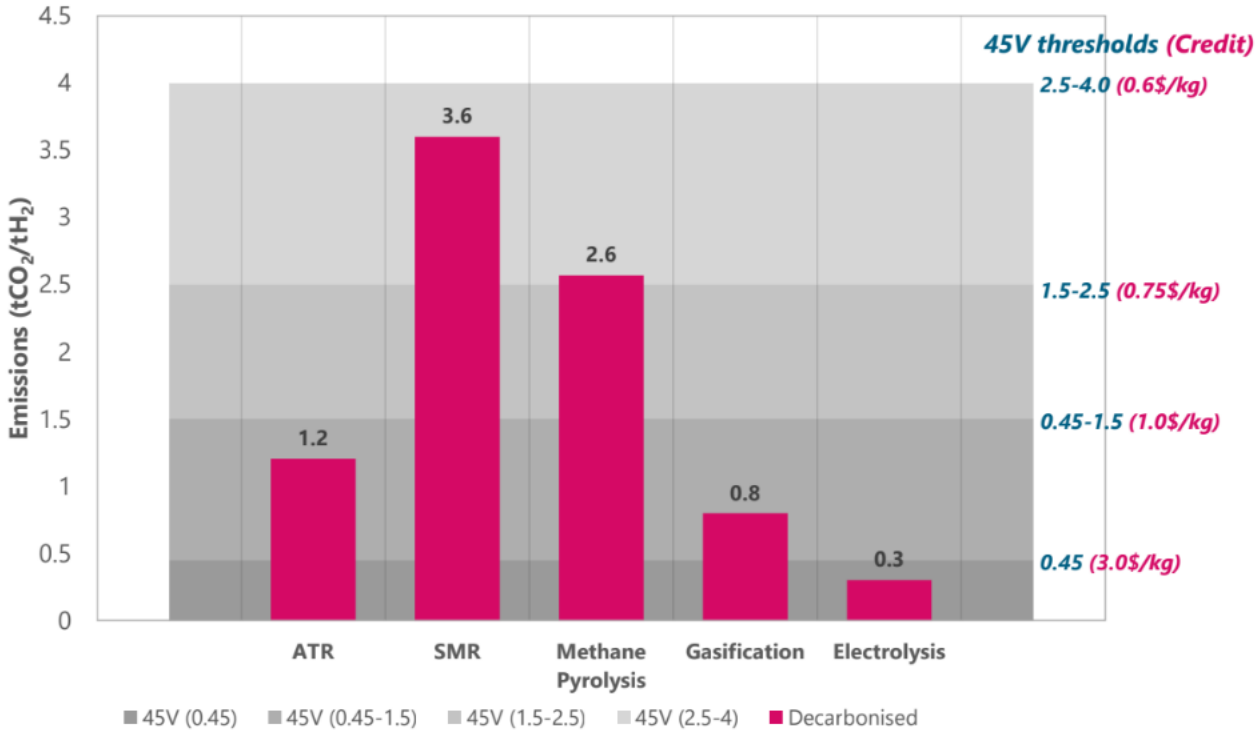
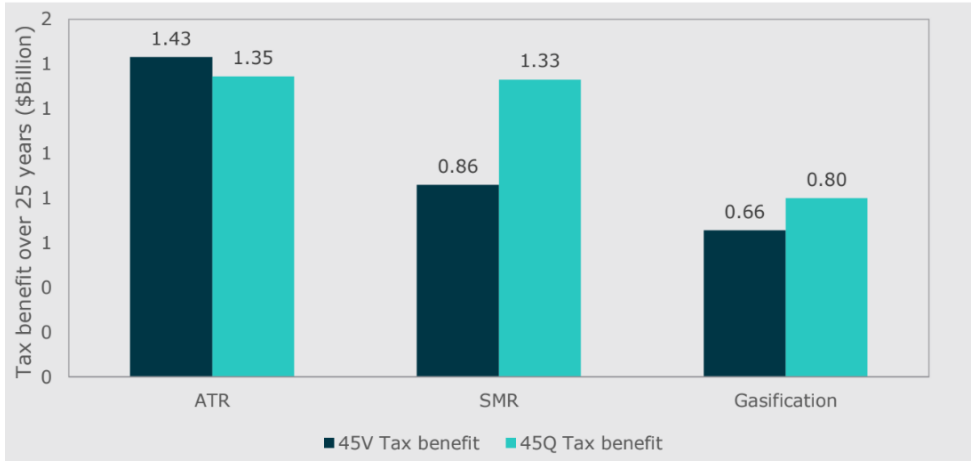
Tax Credit Application

Under the specified set of GHG reduction assumptions in this study, all the low carbon hydrogen production technologies, once abated, qualify for varying degrees of tax credits under the 45V thresholds. However, 45Q is likely to provide larger benefits for some technologies.





Note: Renewable Grid CI 0.005 tCO_2/MWh aligned with Evolved Energy ADP 2022; 50% feed emissions decarbonisation (ex. Gate)

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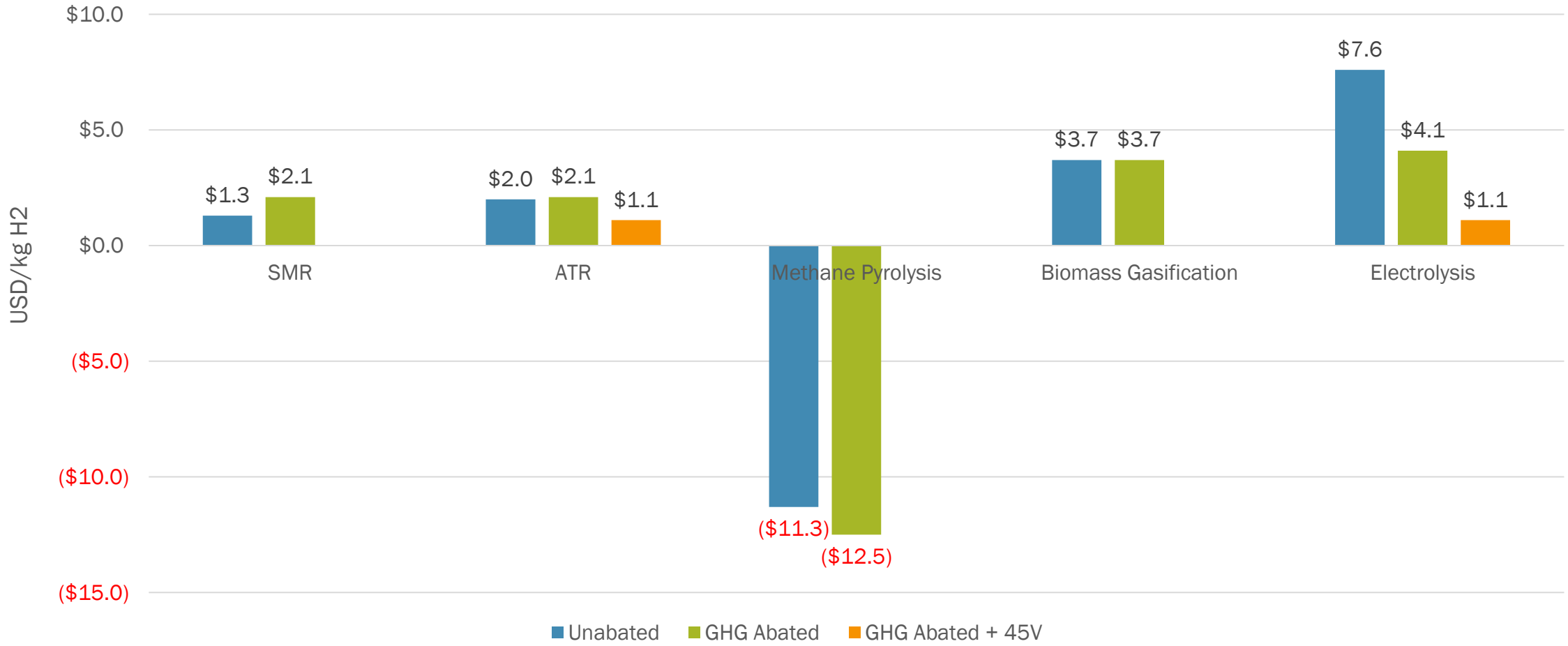
Levelized Cost of Hydrogen



* Tax benefits from 45Q not shown for SMR, methane pyrolysis, and biomass gasification

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Example Technology Deep Dive: SMR

For each technology, the report provides a deep dive on process, material and utility balance, and emissions balance. The report then describes in detail the abatement options and potential.

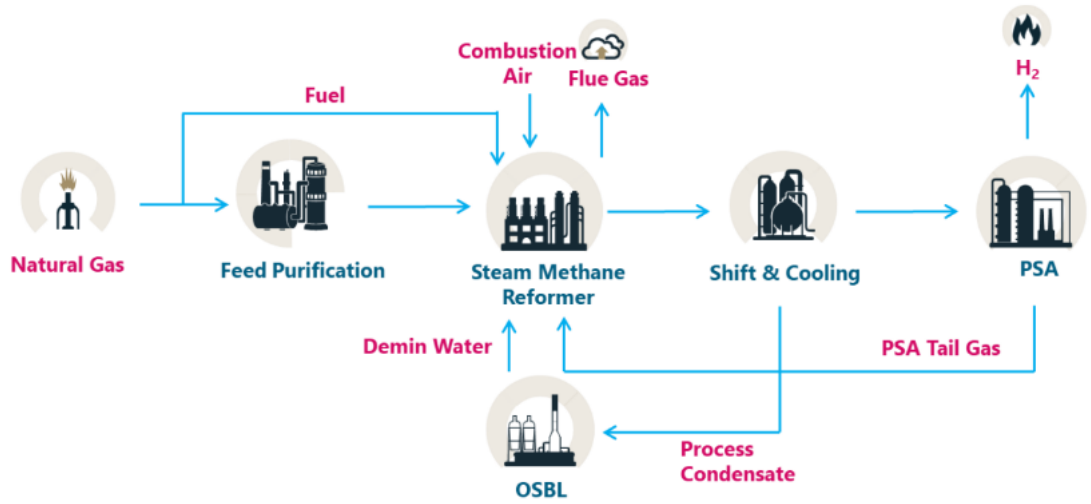

Figure 3-5 Steam Methane Reforming Process Flow Diagram (PFD)

Table 4-1 Abatement Options – SMR

Abatement Option	Description
Process optimization	Focus on improving energy efficiency of the existing operation. This may also include investment to improve equipment or configuration.
Low carbon electricity supply – Renewable Electricity	Replacing the current grid sourced electricity with a renewable or zero carbon alternative will result in reduced emissions. Zero carbon electricity will come at a higher cost which will be discussed later in the report.
Carbon capture – post combustion	Carbon capture on flue gas from the SMR furnace at 95% efficiency. The energy requirement for CCS is assumed to be met by waste heat from the SMR, and that additional steam required is met by an electric boiler that is using zero-emissions electricity.

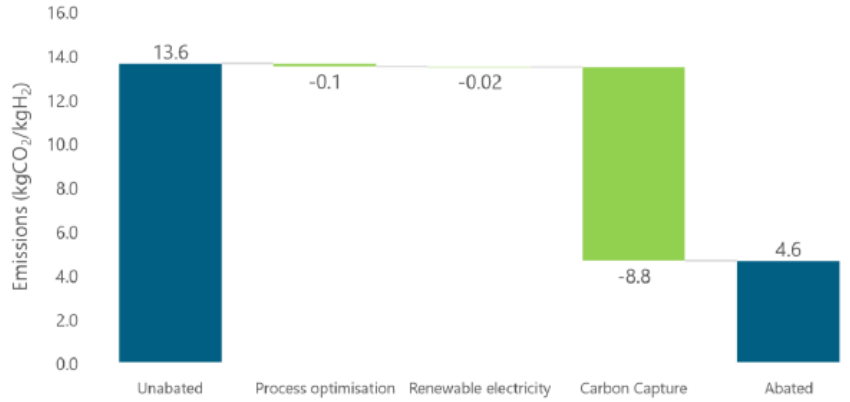

Figure 4-4 Emissions reduction – SMR

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APPENDIX

Production Cost Deep Dive

The levelized cost of unabated hydrogen is broken down for the five different technology pathways. The levelized cost is impacted by the assumptions around utility costs and the value of additional by-products. In addition, the report includes sensitivity cases where the prices of natural gas, carbon black, biomass, and electricity are adjusted.

Table 5-1 Base Case 2023 Operating Expenses, Revenue streams and CAPEX

Parameter	SMR	ATR	Methane Pyrolysis	Biomass Gasification	Electrolysis
Hydrogen Production (tpd)	**358**	**358**	**79**	**164**	**43**
OPEX (2023 USD Millions)	**$107**	**$134**	**$114**	**$83**	**$68**
Electricity (grid)	$1	$20	$38	$15	$61
Natural Gas (Process and/or Fuel)	$96	$92	$55		
Water	$2	$3		$1	<$1
Biomass				$23	
O&M	$8	$19	$20	$43	$7
Other Revenue (2023 USD Millions)					
Carbon Black			$365		
Oxygen					$66
CAPEX (2023 USD Millions) [1]	**$286**	**$651**	**$506**	**$740**	**$242**
CAPEX/Production (2023 USD Millions/tpd H_2)	**$0.8**	**$1.8**	**$6.4**	**$4.5**	**$5.6**
Levelized Cost of Hydrogen (USD/kg H_2) [2]	**$1.3**	**$2.0**	**-$11.3**	**$3.7**	**$7.6**

Note 1 – Class V CAPEX Estimates.
Note 2 – LCOH is calculated from 2027 construction start date, 25 years operation, from 2030 (Inflation applied).

Production Cost Deep Dive: Abated

Abated production costs are shown below.

Table 5-2 Low GHG Technology Scenario - Operating Expenses, Revenue, CAPEX and LCOH

Parameter	SMR	ATR	Methane Pyrolysis	Biomass Gasification	Electrolysis
Hydrogen Production (tpd)	358	358	79	164	43
OPEX (2023 USD Millions)	**$130**	**$127**	**$90**	**$73**	**$29**
Electricity (Renewable)	$11	$10	$14	$7	$22
Natural Gas (Process and/or Fuel)	$96	$92	$55		
Water	$2	$3		$2	>$1
Biomass				$23	
O&M	$21	$21	$20	$41	$7
Other Revenue (2023 USD Millions)					
Carbon Black			$365		
Oxygen					$66
CAPEX (2023 USD Millions) (1)	**$741**	**$738**	**$506**	**$783**	**$242**
CAPEX/Production (2023 USD Millions/tpd H_2)	**$2.1**	**$2.1**	**$6.4**	**$4.8**	**$5.6**
Levelized Cost of Hydrogen (USD/kg H_2) (2)	**$2.1**	**$2.1**	**-$12.5**	**$3.7**	**$4.1**

Note 1 – Class V CAPEX Estimates.
Note 2 – LCOH is calculated from 2027 construction start date, 25 years operation, from 2030 (Inflation applied).

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Production Cost Deep Dive: Sensitvities

Sensitivities included carbon black and electricity prices. The levelized cost of hydrogen when the carbon black product is shown at the base case price of US$1,880, then lowered by 50% and then 100% to simulate a “no demand” case. Electrolysis is analyzed at a forecasted grid price of $79 / MWh as well as various alternative electricity prices (via grid or direct on-site renewables.

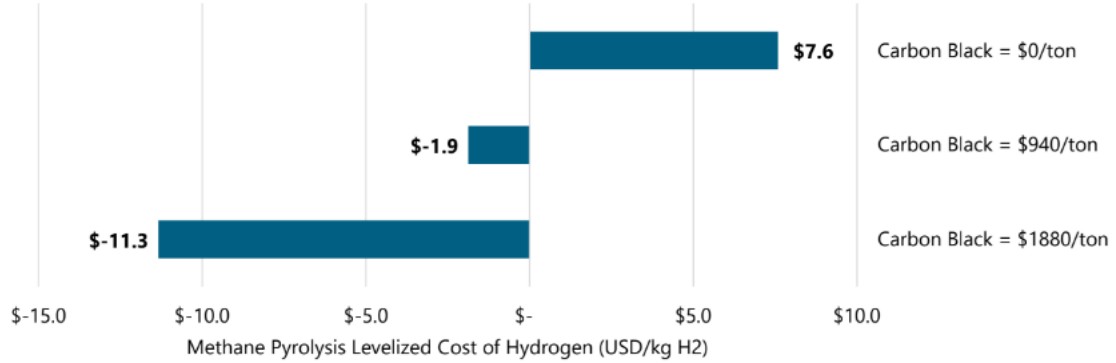

Figure 5-2 LCOH Carbon Black Price Sensitivity Cases.

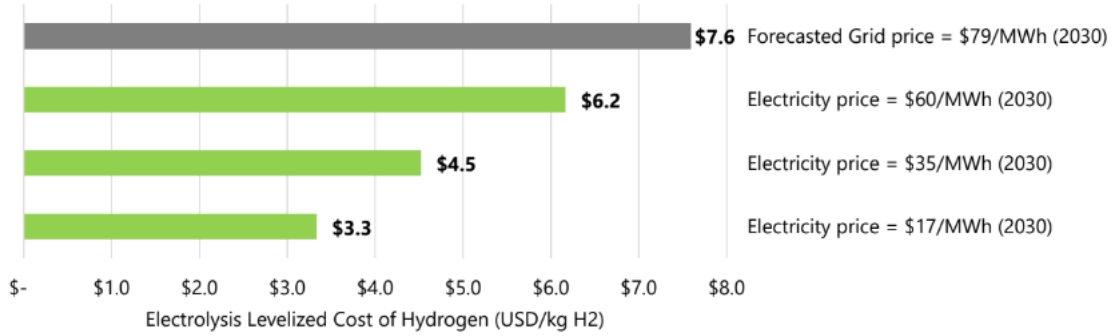

Figure 5-4 LCOH Electrolyzer Electricity Price Sensitivity Cases

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Production Cost Deep Dive: Key Assumptions

Price Assumptions			
Parameter	**Units**	**Value**	**Source**
Natural Gas (LHV)	$/MMBtu	AEO Price Forecast	EIA (2023)
Electricity (Grid 2030)	$/MWh	79	EIA (2023)
Renewable Electricity (PPA 2023)	$/MWh	25	EMB / IEA (2023)
Biomass (2023 basis - Woodchips)	$/t	35	Statista (2023)
Oxygen (2023 basis)	$/t	580	IEA (2023)
Water (2023 basis)	$/t	1.9	Worley Consulting Internal
Carbon Black (2023 basis)	$/t	1880	Worley Consulting Internal
Plant Life	Years	25	Worley Consulting Internal
Plant Construction Start Year	Year	2027	Worley Consulting Internal
Plant Construction Completion Year	Year	2030	Worley Consulting Internal
Discount Rate	%	8%	Worley Consulting Internal
Price Inflation [42]	% pa	2%	Worley Consulting Internal
Natural Gas Inflation	% pa	0.5%	Worley Consulting Internal
Power/Electricity Inflation	% pa	1.6%	EIA (2022-2050)
Carbon Transport & Storage (2023 basis)	$/t	10	NETL (2023)

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